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## Photometric Calibration of the Supernova Legacy Survey Fields

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**Abstract.** The 5-year project Supernova Legacy Survey (SNLS) delivers  $\sim 100$  Type-Ia supernovae (SNe Ia) per year, in the redshift range  $0.3 < z < 1.0$ , with well-sampled  $g'r'i'z'$  lightcurves. The SNLS Collaboration uses the  $1 \text{ deg}^2$  Megacam imager ( $36 \times 2048 \times 4612$  thinned CCDs) mounted on the 3.6-m Canada-France-Hawaii Telescope (CFHT) to observe four fields around the sky, in four filters. The primary goal of the project is to measure the dark energy equation of state with a final statistical precision of  $\pm 0.05$ . We have shown, using the first year dataset that the calibration uncertainties are currently the dominant contribution to the systematic error budget.

The calibration of the SNLS dataset is challenging in several aspects. First, Megacam is a wide-field imager, and only a handful of its 36 CCDs can be directly calibrated using standard star observations. Second, measuring the rest-frame  $B$ -band luminosity of SNe Ia over the  $0.3 < z < 1.0$  redshift range requires an excellent flux intercalibration of the Megacam bands. Finally, the SN Ia SED differs significantly from that of stars and transferring the stellar calibration to the SNLS data requires a precise knowledge of the SN Ia spectra and the instrument transmissions.

We present and discuss the SNLS calibration strategy used to analyze the first year data set. We present the calibration aspects which impact most the cosmological measurements. We also discuss the intercalibration of the SNLS with other surveys, such as the CFHTLS-Wide and the SDSS.

### 1. The Supernova Legacy Survey

Type Ia supernovae (SNe Ia) are a powerful probe of the history of cosmic expansion. The first distant SN Ia surveys (Perlmutter et al. 1997, 1999; Riess et al. 1998) detected the acceleration of the expansion, and provided strong evidence for repulsive dark energy driving the expansion. Subsequent surveys (Knop et al. 2003; Tonry et al. 2003; Barris et al. 2004; Riess et al. 2004) confirmed this result. Determining the nature of dark energy by measuring its equation of state, i.e. its pressure over density ratio:  $w = p/\rho$  has now become a central question in observational cosmology. Many dark energy models have been proposed, besides the historical cosmological constant ( $w = -1$ ). Some of them predict values of  $w$  significantly different from  $-1$ . Unfortunately, the best constraints

obtained from the SNe Ia surveys mentioned above are consistent with a wide range of dark energy models.

Improving them to the point where  $w = -1$  could be excluded or confirmed requires a ten-fold larger sample, i.e.  $O(1000)$  SNe at  $0.3 < z < 1.0$ —where  $w$  is best measured—in order to improve not only on statistics, but also on systematics. Several second-generation surveys have been designed to build such samples: the Supernova Legacy Survey (SNLS), at the Canada-France-Hawaii Telescope (CFHT), and the ESSENCE project at the Cerro-Tololo InterAmerican Observatory.

The Supernova Legacy Survey delivers  $\sim 100$  SNe Ia per year, with well sampled  $g'r'i'z'$  lightcurves. Over the five year duration of the project, we expect to obtain several hundred SNe Ia, all spectroscopically identified. The SNLS project is comprised of two components: a large imaging survey to detect supernovae and monitor their lightcurves, and a spectroscopic survey, to confirm the nature of the candidates and measure their redshift.

The imaging survey is a component of the larger CFHT Legacy Survey project (CFHTLS 2002). The CFHTLS operates the one square-degree imager MEGACAM (Boulade et al. 2003) mounted on the prime focus of the Canada France Hawaii Telescope, and has been allocated 474 nights over 5 years. The whole project actually consists of 3 distinct surveys: a very wide shallow survey (1300 square degrees), a wide survey (120 square degrees) and a deep survey (4 square degrees). The 4 pointings of the deep survey (Table 1) are evenly distributed in right ascension, and observed at five equally space epochs during a Megacam Run, which lasts at least 14 nights around new moon. The observations are taken in a combination of the  $r$ ,  $i$  plus  $g$  and  $z$  megacam filters, depending of the phase of the moon.

Field	RA(2000)	Dec(2000)	$E_{B-V}$ (MW)
D1	02:26:00.00	−04:30:00.0	0.027
D2	10:00:28.60	+02:12:21.0	0.018
D3	14:19:28.01	+52:40:41.0	0.010
D4	22:15:31.67	−17:44:05.0	0.027

Table 1. Coordinates and average Milky Way extinction (from Schlegel et al. 1998) of fields observed by the Deep/SN component of the CFHTLS.

From the first year of operations, we obtained 71 type Ia supernovae spectroscopically identified and well sampled enough to be placed on a Hubble diagram. Using this unique data set, supplemented with 41 published low-redshift SNe Ia, we have built a Hubble diagram extending to  $z = 1$ , with all distance measurements involving at least two bands (Astier et al. 2006). The cosmological fit to this first year SNLS Hubble diagram gives the following results :  $\Omega_m = 0.263 \pm 0.042$  (*stat*)  $\pm 0.032$  (*sys*) for a flat  $\Lambda$ CDM model; and  $w = -1.023 \pm 0.090$  (*stat*)  $\pm 0.054$  (*sys*) for a flat cosmology with constant equation of state  $w$ , when combined with the constraint from the recent Sloan Digital Sky Survey measurement of baryon acoustic oscillations. This is currently the best available constraint on the dark energy equation of state.

Improving significantly this result requires to push down the systematic uncertainties. In Astier et al. (2006) we have shown that photometric calibration is currently the dominant source on the cosmological parameter error budget. In the following of this paper we discuss our current calibration strategy, and our efforts to improve the calibration of the survey. In section 2., we present the photometric calibration constraints of a supernova survey. We then describe the Megacam imager (section 3.). We describe the calibration of the first year data (section 4.). Finally, we discuss our current efforts to calibrate the SNLS survey using Sloan and HST secondary and primary standards, which should allow us to cross-check the Vega/Landolt zero-points, and more accurately calibrate  $z$ -band observations.

## 2. Calibrating a Dark-Energy Survey

Currently broadband photometric measurements are calibrated using observations of reference standard stars, which define a photometric system (see Landolt 1992; Smith et al. 2002). Most photometric systems are ultimately tied to the SED of Vega. However, since Vega is  $10^6$  times brighter than the mag 15 secondary standards currently used by large telescopes, the path from the Vega SED determination to the zero points of modern standard star catalogs is rather indirect. This can lead to systematic errors of a few percent when trying to convert magnitudes into fluxes (Fukugita et al. 1996).

In supernova cosmology, we study the luminosity-distance-versus-redshift-relation,  $d_L(z)$ . In order to measure the luminosity distance of a supernova, we have to *infer* its apparent peak brightness at some chosen reference wavelength in the supernova *rest-frame*, using photometric measurements performed at a few fixed passbands in the observer frame. Such a transformation is called a  $k$ -correction. In order to  $k$ -correct supernova magnitudes, we need the following ingredients:

1. the zero points of the photometric system used to calibrate our measurements, in order to convert calibrated magnitudes into fluxes. Depending on how the magnitude system was tied to the SED of the fundamental flux standard (such as Vega), this step can be one of the dominant sources of systematic errors on the cosmological measurements. Note however that only the band-to-band relative values of the zero points have an impact on cosmology (i.e. the Vega colors in the photometric system used to calibrate the measurements).
2. a model of the instrument passbands including the transmission of the optics, the mirror reflectivity, the filter transmissions, the CCD quantum efficiency and finally, a model of the atmospheric absorption, especially in the near infrared, where atmospheric absorption lines are rather strong and in the near-UV.
3. a model of the effective passbands of the photometric system used to calibrate the survey. These passbands usually differ from those which equip the survey telescope.

4. a model of the supernova SED as a function of time (see for example Guy et al. 2005). We won't address this issue here.

The supernovae discovered by the SNLS cover the  $0.3 < z < 1.0$  redshift range. This dataset must be supplemented by an additional set of SNe Ia at much lower redshift ( $z \sim 0.05$ ), in order to extract precise measurements of the cosmological parameters from a Hubble diagram. Most well studied nearby SNe Ia were discovered by (Hamuy et al. 1996; Riess et al. 1999) and others during the last decade, and calibrated in the photometric system defined by (Landolt 1992). We therefore have to adopt the same calibration source for the SNLS sample. This avoids introducing additional systematic uncertainties between the distant and nearby SN fluxes. However, this is complicated by the fact that the Megacam passbands differ significantly from the *UBVRI* filters used by Landolt.

### 3. The Megacam Imager

Megacam is a wide-field imager, built by the Commissariat à l'Énergie Atomique (CEA) for the prime focus of the 3.6-m Canada France Hawaii telescope. It covers a field area of  $0.96 \times 0.94 \text{ deg}^2$ , with an excellent and remarkably uniform image quality. The focal plane is made of 36 thinned  $2048 \times 4612$  CCDs, with pixels of  $13.5 \mu\text{m}$  that subtend  $0.18 \text{ arcsec}$  on a side. The whole focal plane comprises  $\sim 340$  million pixels. However, it is read in less than 40 seconds. Each CCD is read out from two amplifiers.

Great care has been taken in the internal calibration of the imager. Indeed, any not accounted-for shutter imperfection or non-linearity of the detector/electronics can bias the measurements and hence the cosmology. Another potential source of problems is the uniformity of the camera: we cannot afford to calibrate each of the 36 CCDs using standard star observations. Most standard stars are therefore observed with the center CCDs, and the camera non-uniformities of the photometric response are carefully modeled. Any residual radial non-uniformities of the photometric response may distort the supernova luminosity distribution, and bias the cosmological measurements. In this section, we review the critical camera systems. In the next section, we will present the photometric calibration procedure.

*The Shutter system* The shutter precision is a potential source of systematic uncertainties, given (1) the possible non uniformities due to the shutter motion and (2) the exposure time differences between the calibration exposures (a few seconds) and the science exposures (hundreds of seconds). The shutter system was carefully designed in order to ensure that (1) the accuracy of the exposure time measurement is better than 1 ms and (2) the uniformity of the exposure time is to better than 1%. The design of the shutter is based on the controlled rotation of a half disk, — one meter in diameter — in order to ensure a constant speed when the shutter crosses the CCD mosaic. The exact duration of the exposure time is measured with a precision of 0.5 ms with a dedicated system independent from the shutter motion controller. The shutter precision was investigated by the CFHT team. It was shown that the non-uniformity due to

the shutter is below 0.3% accross the mosaic. The systematic flux differences between the exposures were found to be below 1% (r.m.s.).

*Linearity* The linearity of the CCDs and the readout electronics is also a potential source of systematic uncertainties. The requirements stated that the linearity of each channel had to be better than 1%. The linearity was later investigated by the CFHT team. It was found to be within the specifications, except for CCD#17.

*Filters* The filter system is a juke box which holds up to 8 filters. The CFHT Legacy Survey performs observations in five bands, labeled  $u_M, g_M, r_M, i_M, z_M$ , similar to the SDSS  $u'g'r'i'z'$  bands. The SNLS uses only the  $g_M, r_M, i_M$ - and  $z_M$ -band observations. The filters currently mounted on Megacam are interferometric filters manufactured by REOSC/Sagem. Their transmissions were characterized by the manufacturer and the CFHT team. Small systematic differences were found between the Megacam and SDSS filters, which translate into small color terms between both instruments (see below).

## 4. The Photometric Calibration Procedure

### 4.1. Elixir Pipeline. Uniformity of the Photometric Response

At the end of each CFHT run, the raw images are processed using the Elixir pipeline, developed by the CFHT team (Magnier & Cuillandre 2004). Master flat field images and fringe corrections are built from all the data taken during the run, including PI data. The Elixir pipeline applies these flat fields to the data, subtract the fringe patterns and determines an astrometric solution.

Flat-fielding ensures that the pixel-to-pixel response is uniform accross the entire focal plane. However, it was found that the photometric response measured on flat-fielded images was not uniform. In other words, two measurements of the same star, at two different locations of the focal plane, may yield different instrumental fluxes. These non-uniformities have been measured using dithered observations of dense stellar fields, and have been found to be radial and as large as 15% (Fig. 1). These observed non-uniformities may have a number of explanations, and a combination of explanations is likely. One is the geometric distorsion: a pixel at the center of the field subtends a different solid angle on the sky than a pixel located on the edges. The flat field provides a uniform illumination, and does not account for this effect. However, such an effect would be achromatic, which is not the case here. Moreover, the amplitude of the geometric distorsion, which can be determined from the astrometry only accounts for half of the observed effect. Another possible explanation is scattered light during the flat field observations.

Modeling scattered light, or removing it totally is extremely difficult. Therefore the CFHT team has chosen to measure the non-uniformities of the photometric response using the dense stellar field dithers mentioned above, and to include this model into the flat field corrections. The Elixir team has deliberately chosen to provide reduced data which has a uniform photometric response accross the mosaic, at the expense of a non-uniform sky background.

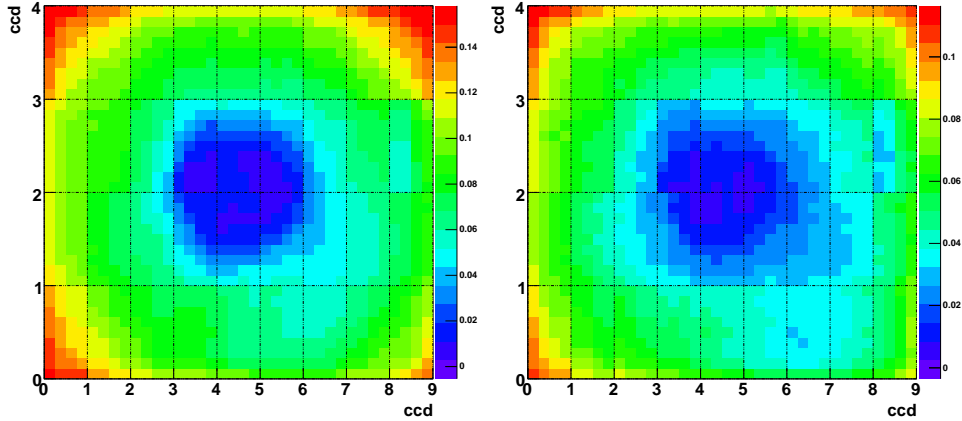


Figure 1. Map of the non-uniformities of the photometric response, in the  $r$ -band (left) and  $i$ -band (right). Each map represents the whole focal plane. The grids materialize the CCDs. The maps are determined using dithered exposures of a dense stellar field. Each CCD is divided into  $4 \times 9$  cells. Since each star of the dense stellar field is observed on several cells during the dithering sequence, we are able to intercalibrate each cell with respect to a cell chose as a reference.

In order to improve significantly the measurements published in (Astier et al. 2006), SNLS has started an ambitious program to decrease the internal calibration uncertainties down to 1%. A considerable amount of work is therefore still being carried out on this subject by the Elixir and SNLS teams. In particular, the dense stellar field dithers are being reanalyzed by both teams using different methods, in order to improve the photometric correction function, and to investigate potential non-uniformities in the filter passbands.

#### 4.2. Building Tertiary Standard Catalogs

The images preprocessed by the Elixir pipeline have a flat photometric response. Each image has then to be aligned on the Landolt catalog. We have chosen to proceed in two steps: first, we have built a catalog of so called tertiary standards, i.e. science field stars whose fluxes have been calibrated using Landolt star observations. Then, using this catalog, each image containing tertiary standards can be calibrated.

Building a tertiary standard catalog is relatively easy since we have between 12 and 25 epochs (depending on the passband: 12 in  $g_M$  and  $z_M$  and over 20 in  $r_M$  and  $i_M$ ) for each science field, and since both standard and science fields were repeatedly observed. Photometric nights were selected using the CFHT “Skyprobe” instrument (SkyProbe 2003), which monitors atmospheric transparency in the direction that the telescope is pointing. Only the 50% of nights with the smallest scatter in transparency were considered. For each night, stars were selected in the science fields and their aperture fluxes measured and corrected to an airmass of 1 using the average atmospheric extinction of Mauna Kea. These aperture fluxes were then averaged, allowing for photometric ratios between exposures of the same night. Stable observing conditions were indicated by a very small scatter in these photometric ratios (typically 0.2%); again the

averaging was robust, with  $5\text{-}\sigma$  deviations rejected. Observations of the Landolt standard star fields were processed in the same manner, though their fluxes were not averaged. The apertures were chosen sufficiently large (about  $6''$  in diameter) to bring the variations of aperture corrections across the mosaic below 0.005 mag. However, since fluxes are measured in the same way and in the same apertures in science images and standard star fields, we did not apply any aperture correction.

Using standard star observations, we first determined zero-points by fitting linear color transformations and zero-points to each night and filter, however with color slopes common to all nights. In order to account for possible non-linearities in the Landolt to MegaCam color relations, the observed color-color relations were then compared to synthetic ones derived from spectrophotometric standards. This led to shifts of roughly 0.01 in all bands other than  $g_M$ , for which the shift was 0.03 due to the nontrivial relation to  $B$  and  $V$ .

We then applied the zero-points appropriate for each night to the catalog of science field stars of that same night. These magnitudes were averaged robustly, rejecting  $5\text{-}\sigma$  outliers, and the average standard star observations were merged. Figure 2 shows the dispersion of the calibration residuals in the  $g_M$ ,  $r_M$ ,  $i_M$  and  $z_M$  bands. The observed standard deviation, which sets the upper bound to the repeatability of the photometric measurements, is about or below 0.01 mag in  $g_M$ ,  $r_M$  and  $i_M$ , and about 0.016 mag in  $z_M$ .

For each of the four SNLS fields, a catalog of tertiary standards was produced using the procedure described above. The dominant uncertainty in the photometric scale of these catalogs comes from the determination of the color-color relations of the standard star measurements. For the  $g_M$ ,  $r_M$  and  $i_M$  bands, a zero-point offset of 0.01 mag would easily be detected; hence we took this value as a conservative uncertainty estimate. The  $z_M$  band is affected by a larger measurement noise, and it is calibrated with respect to  $I$  and  $R - I$  Landolt measurements. We therefore attributed to it a larger zero point uncertainty of 0.03 mag.

Once magnitudes are assigned to tertiary standards, supernova magnitudes are measured by estimating the supernova flux and the field stars (i.e. the tertiary standard) fluxes with the same PSF photometry. Although supernovae involve a differential photometry and field stars do not, we were able to prove that the possible biases of the supernova to field stars flux ratios are negligible (see Astier et al. 2006)

*Megacam Filter Model* For the MegaCam filters, we used the measurements provided by the manufacturer, multiplied by the CCD quantum efficiency, the MegaPrime wide-field corrector transmission function, the CFHT primary mirror reflectivity, and the average atmospheric transmission at Mauna Kea. As an additional check, we computed synthetic MegaCam-SDSS color terms using the synthetic transmissions of the SDSS 2.5-m telescope (SkyServer 2004) and spectrophotometric standards taken from (Pickles 1998; Gunn & Stryker 1983). Since the SDSS science catalog (Finkbeiner et al. 1994; Raddick 2002; SkyServer 2004) shares thousands of objects with two of the four fields repeatedly observed with MegaCam, we were able to compare these synthetic color transformations with the observed transformations. We found a good agreement, with uncertain-



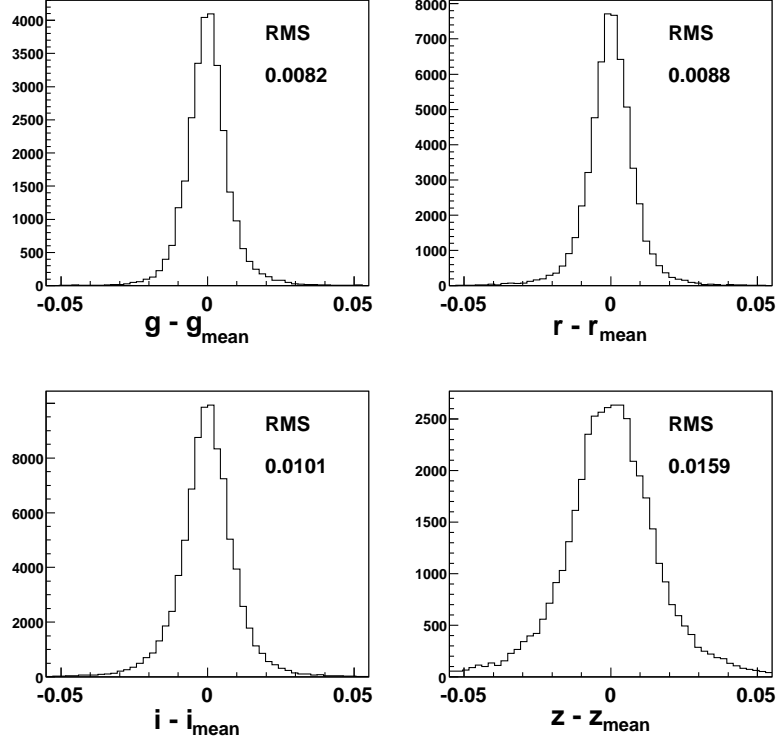


Figure 2. The calibration residuals — *i.e.* the residuals around the mean magnitude of each Deep field tertiary standard— in the bands  $g_M$ ,  $r_M$ ,  $i_M$  and  $z_M$ , for all CCDs and fields, with one entry per star and epoch. The dispersion is below 1% in  $g_M$ ,  $r_M$  and  $i_M$ , and about 1.5% in  $z_M$ .

ties at the 1% level. This constrains the central wavelengths of the MegaCam band passes to within 10 to 15 Å with respect to the SDSS 2.5m band passes.

*Landolt Effective Filter Model* The choice of filter band passes to use for Landolt based observations is not unique. Most previous supernova cosmology works assumed that the determinations of (Bessell 1990) describe the effective Landolt system well, although the author himself questions this fact, explicitly warning that the Landolt system “*is not a good match to the standard system*” — *i.e.* the historical Johnsons-Cousins system. Fortunately, (Hamuy et al. 1992, 1994) provide spectrophotometric measurements of a few objects measured in (Landolt 1992); this enabled us to compare synthetic magnitudes computed using Bessell transmissions with Landolt measurements of the same objects. This comparison reveals small residual color terms which vanish if the  $B$ ,  $V$ ,  $R$  and  $I$  Bessell filters are blue-shifted by 41, 27, 21 and 25 Å respectively. Furthermore, if one were to assume that the Bessell filters describe the Landolt system, this would lead to synthetic MegaCam-Landolt color terms significantly different from the measured ones; the blue shifts determined above bring them into excellent agreement. We therefore assumed that the Landolt catalog magnitudes

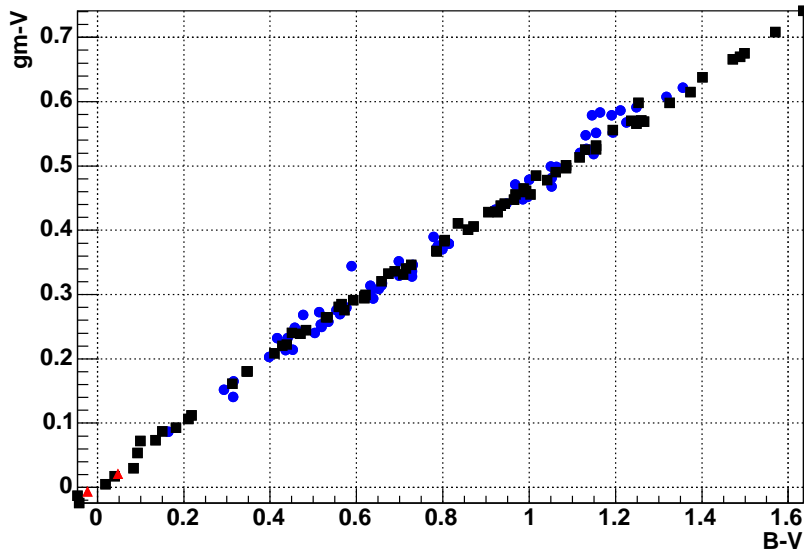


Figure 3.  $g_M - V$  vs.  $B - V$  color-color plots, built from (1) Megacam observations of Landolt stars (blue dots) (2) synthetic  $g_M, B, V$ -band magnitudes computed using our passband models and spectra taken from (Gunn & Stryker 1983) (red dots) and (Pickles 1998) (black dots).

refer to blue-shifted Bessell filters, with a typical central wavelength uncertainty of 10 to 15 Å, corresponding roughly to a 0.01 accuracy for the color terms.

A powerful check of (1) our alignment on the Landolt system (2) our model of the Megacam passbands and (3) our model of the effective Landolt filters is to compare observed and synthetic color-color plots, using our observations of the Landolt stars and synthetic Landolt and Megacam magnitudes of stellar spectra. Figure 3 presents the  $g_M - V$  vs.  $B - V$  diagram built from (1) Megacam observations of Landolt stars (blue dots) (2) synthetic  $g_M, B, V$ -band magnitudes computed using our passband models and spectra taken from (Gunn & Stryker 1983) (red dots) and (Pickles 1998) (black dots). We notice an excellent agreement between the synthetic and observed magnitudes.

## 5. Improving the Calibration Path

As discussed in section 2., the current calibration program is not optimal for supernova cosmology: we know little about the systematic uncertainties associated with converting Landolt magnitudes into fluxes, and there is no official determination of the Landolt passbands. Finally, the  $z_M$ -band is redder than the reddest Landolt band ( $I$ ). Therefore, the Megacam to Landolt  $z$  to  $I$  transformation is an extrapolation, based on the sampling of the main sequence stars published by (Pickles 1998; Gunn & Stryker 1983).

The calibration landscape is rapidly evolving, and quickly getting much richer and redundant. The set of HST flux standards, aligned on the white

dwarf flux scale (Bohlin et al. 2004; CALSPEC Database 2006) is constantly expanding, and includes fundamental calibrators such as Vega (Bohlin & Gilliland 2004a) and BD +17 4708 (AB fundamental standard) (Bohlin & Gilliland 2004b). The SDSS 2.5-m system which has become a de-facto standard photometric system is slowly being tied to the white dwarf flux scale.

The SNLS collaboration has therefore started a dedicated effort to produce a definitive set of tertiary standards, calibrated against these new sets of standards. This effort consist in observing in all bands a dithered sequence of the SNLS fields, parts of the well calibrated SDSS Southern Strip, Landolt calibrators and HST fundamental standards. The dither sequence will allow us to check the uniformity of the photometric response, and detect possible variations of the amplifier gains at the sub-percent level. The combination of celestial calibrators will permit to calibrate the tertiary standards against several important magnitude systems, and to check for systematic differences between those systems.

## 6. Conclusion

The calibration of the SNLS dataset is challenging in several aspects. First, Megacam is a wide field imager, and controlling the uniformity of such an instrument is not possible without a dedicated calibration program. We have shown in section 4. that not accounted-for non-uniformities can bias the cosmological measurements. Another difficult task is to control how the Landolt system is tied to Vega, its fundamental flux standard. We have therefore embarked in two distinct programs to (1) control the internal calibration of our imager with a precision better than 1% and (2) check our current calibration path. A longer term goal is to define an absolute flux calibration of the SNLS survey, based on the white dwarf flux scale. The photometric calibration work currently carried out will allow us to reach the 1% precision which must be attained to significantly improve the measurements of the cosmological parameters.

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